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ORIGINAL PAPER

Stratigraphy and structural style of Souk Ahras foreland fold-thrust belt in northeastern Algeria

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Abstract
In northeastern Algeria, the Souk Ahras foreland basin is a part of the Maghrebides fold-thrust belt and comprises Sellaoua and Medjerda High units in the footwall of Tellian thrust sheets. Detailed geological mapping supported by micro-paleontological, petrographic, and structural data allows us to reappraise its stratigraphy and its structural style and to characterize the relationship between the different structural units (Numidian, Tellian, Sellaoua, and Medjerda High units). Data were collected for a biostratigraphy and field observations along to six (06) sections spread over the Ouled Driss, Dj. Boubakhouch, Dj. Boukebch – Dekma, and the Medjerda High. The Souk Ahras foreland basin substrate is made up by Jurassic and early Cretaceous series and constituted an outer shelf pre-foreland passive margin where salt tectonics occurred. From upper Cretaceous to Miocene, flexural subsidence and thrust wedge propagation took place as the result of the northward drift of Africa plate. The Souk Ahras foreland is finally deformed by thrust-related folds, which affected a pre shortening tectonic pile involving remnant of salt tectonics influenced margin during at least Cretaceous times.

Keywords Maghrebides belt · Souk Ahras foreland · Stratigraphy · Structural style · Fold-thrust belt

Introduction

The Maghrebides fold-and-thrust belt developed on the African lithosphere as subduction process occurred at the Tethys-African northern plate boundary since at least the Oligocene (Frizon de Lamotte et al. 2000, 2009; Bracène and Frizon de Lamotte 2002; Herkat and Guiraud 2006; Marmi and Guiraud 2006; Khomsi et al. 2009; Roure et al. 2012; Leprêtre et al. 2018). Since recent geodynamics can be considered as established, regional works as, detailed mapping and biostratigraphy of underexplored areas, remain essential to the understanding of basin dynamics as a whole.

The Souk-Ahras region belongs to the evaporite bearing foreland of the eastern Maghrebides fold-and-thrust belt (Vila 1980). It is characterized by an imbricate fan of thrust sheets over a detached and folded foreland (Chabbi et al. 2016, 2019) called "Sellaoua unit" (Vila et al. 1995). These thrust-salt structures propagate southwards during the Cenozoic (Vila 1980; Bracène and Frizon de Lamotte 2002; Marmi and Guiraud 2006; Roure et al. 2012; Leprêtre et al. 2018).

Stratigraphy of the Souk Ahras foreland fold-and-thrust belt, which is the aim of the paper, is poorly known and not published. We propose a new sampling of outcropping strata to fix stratigraphic issues and to provide a detailed map of the Souk Ahras area. This study is based on previous published and unpublished works, field geological mapping and micro-paleontological evidences allowing establishing a stratigraphic synthesis of the area.

Geological setting

The geology of Algeria is commonly defined as formed by three systems, which are from south to north: the Sahara, Atlas, and Maghrebides systems (Fig. 1a) to which the study area belongs.

The Maghrebides system develops as an orogenic belt along the North African margin (Morocco, Algeria, and Tunisia),

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Sicily and the Apennines (Fig. 1a) (Durand-Delga 1969, 1980; Vila 1980; Wildi 1983; Bouillin 1986; Frizon de Lamotte et al. 2000, 2009; Bracène and Frizon de Lamotte 2002; Roure et al. 2012; Leprêtre et al. 2018). In Algeria, Maghrebides belt exhibits three tectonic domains, from north to south: (a) the Kabylides (greater and lesser Kabylies) (Fig. 1b, 1c) are mainly made up of Hercynian basement, unconformably covered by continental Triassic red beds, deep to shallow marine Jurassic to Eocene series (Djelit 1987; Roure et al. 2012). The whole is unconformably overlain by molasses of the so-called 'Oligo-Miocene Kabyle' (Benaouali-Mebarek et al. 2006). (b) The "Flyschs zone" develops south of the Kabylides (Fig. 1b and c). It consists of superimposed tubiditic depocenters exhibiting intra-formational unconformities which ranged from Jurassic to Miocene (Durand-Delga 1969, 1980; Lahondère et al. 1979; Bouillin 1986; Riahi et al. 2010; Leprêtre et al. 2018).

(c) The external zones (Fig. 1b, 1c) (Leikine 1971; Vila 1980; Obert 1981; Chouabbi 1987; Lahondère 1987; Chabbi et al. 2019) represent the African paleo-margin of Tethys (Durand-Delga 1969, 1980; Vila 1980; Bouillin 1986; Frizon de Lamotte et al. 2000, 2009; Roure et al. 2012; Leprêtre et al. 2018). In northeastern Algeria, the external zones is considered as a stack of thrust sheets, including the Numidian and Tellian thrust sheets (Vila 1980; Chouabbi 1987; Lahondère 1987; Chabbi 2017; Chabbi et al. 2019), in the footwall of these thrust units, the foreland basin is constituted by, from west to east, the "south-Setifien allochthonous set", the "Constantine unit" and the Sellaoua unit (Voûte 1967; Vila 1980).

The Souk Ahras Foreland fold and thrust belt is formed by four tectonic units covered by Postorogenic deposits (conglomerates, sandstone, red clay of upper Miocene to present day), from south to north we can distinguish (Figs. 2, 3):

- The Medjerda High is a pre-atlasic subunit formed by marine mudstones and limestones of Cretaceous to Paleocene; and nummulitic limestones, conglomerate, and glauconitic argillaceous marl of Eocene age, unconformably covered by Miocene deposits.
- The Sellaoua basin extends between the Tunisian border and Souk Ahras city (Fig. 1b, Fig. 2, Fig. 3), and it continues westward to Aïn Fakroune city (south of Constantine). It displays south-verging thrust-related folds.
- The Tellian thrust sheets consist of Paleocene to Priabonian limestones containing planktonic foraminiferal assemblage in the north and a shallow marine nummulitic assemblage,
- The Numidian thrust sheet exhibit greenish-brownish mudstones in the base followed by thick turbiditic sandstones and a red clays Oligo-Miocene in age.

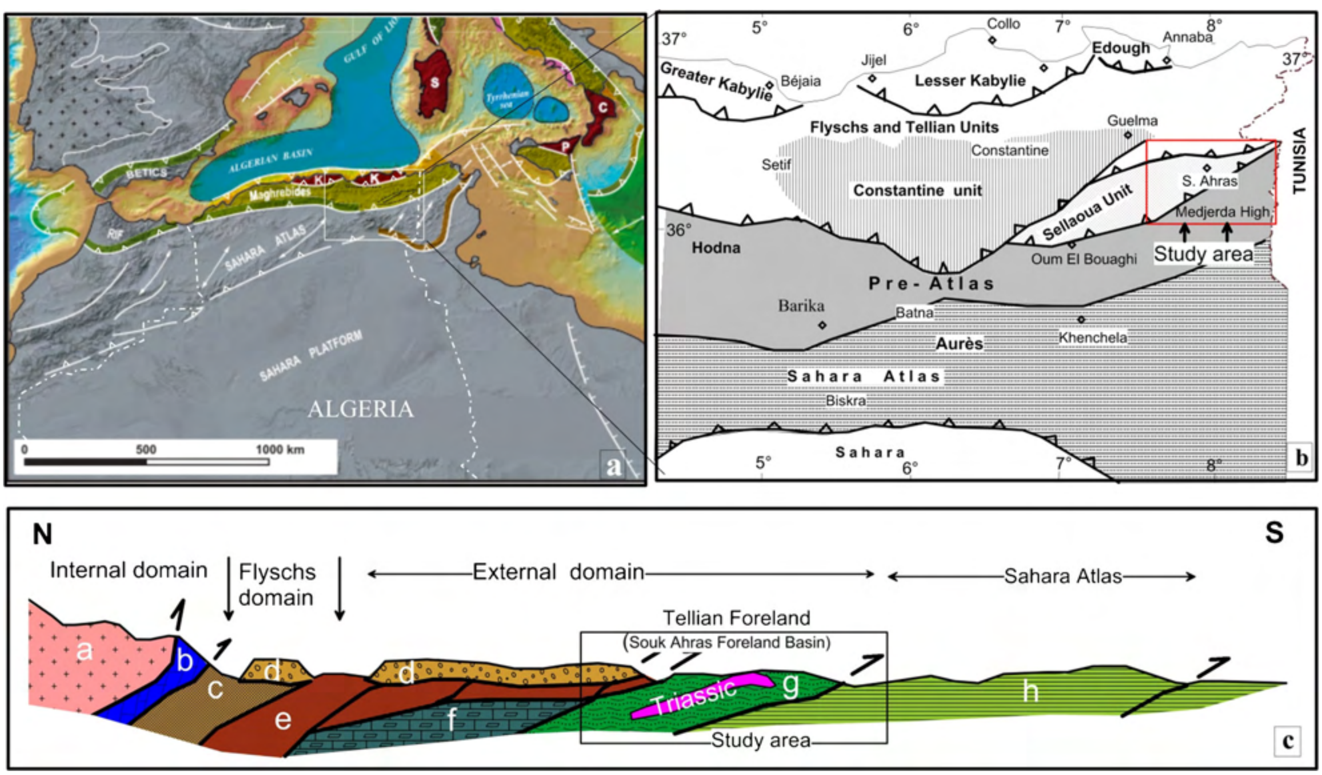


Fig. 1 **a** Geodynamic setting of western Mediterranean sea: structural map showing the three main units of north Algeria (Roure et al. 2012), **b** the main structural domains of northeastern Algeria showing the studied area location, **c** Schematic cross section showing the structure of the Maghrebides thrust belt in Eastern Algeria (modified from (Peybernès et al. 2002)). Legend of (Fig. 1c): **a**. Kabylides massif, **b**. 'Dorsale calcaire' (Dorsale Kabyle), **c**. Mauritanian and Massylian flyschs, **d**. Numidian flyschs, **e**. Tellian thrust sheets, **f**. Constantine Neritic nappe, **g**. Sellaoua foreland, **h**. Pre-Atlasic domain foreland (Medjerda, and Mellègues Highs)

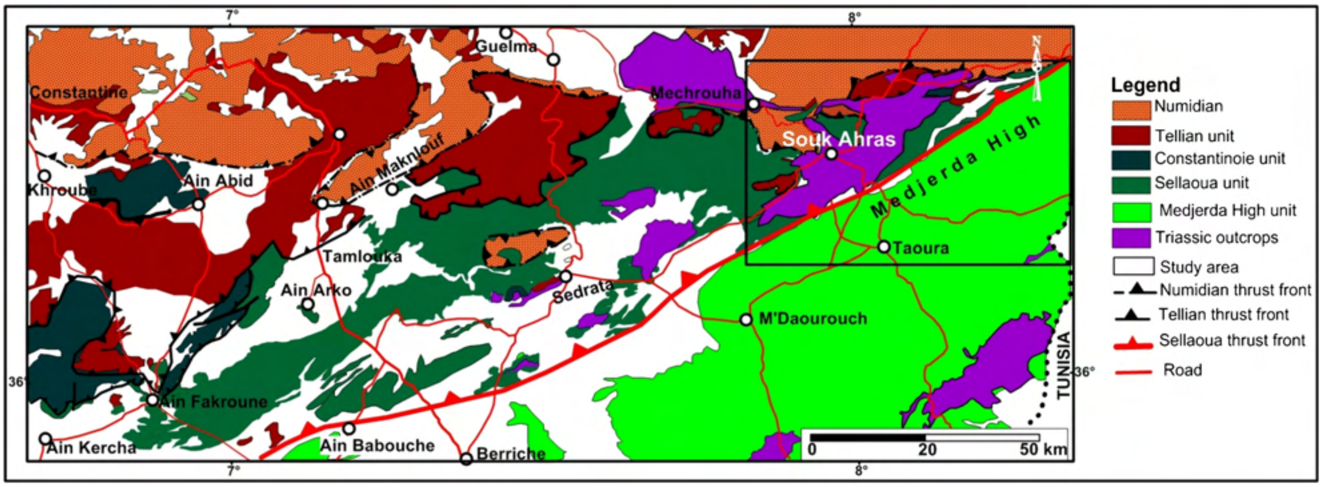


Fig. 2 Regional geological map showing the Souk Ahras foreland fold-and-thrust belt in its regional framework

Materials and methods

In the Souk Ahras foreland, we collected more than one hundred samples of mudstones and limestones along six stratigraphic sections (Fig. 3). Biostratigraphic and petrographic preparations were performed in the Geodynamics and natural resources laboratory (UBMA, Algeria). The preparation of marl samples for biostratigraphic study is carried out according the standard wash raw samples through a column of sieves: 500, 250, 100, and 60 μm. Planktonic and benthic foraminifera and ostracods were picked and determined using a stereoscopic binocular by Dr. Chermiti and Pr. Ben Youssef, (Georesources Laboratory, Water Research and Technology Center Tunisia). Determinations have been completed by reference to the published works of (Bellion et al. 1973; Aubert and Berggren 1976; Salaj 1980; Caron 1985; Toumarkine and Luterbacher 1985; Faid 1999; Chermiti et al. 2018). Conventional mapping has been performed corresponding to around 50 days of surveying in the last 6 years by the corresponding author.

Structural study is based on surface structural data carried out from extended field surveys in the study area and also from geologic maps (Kriviakine et al. 1989a, b, c).

Field data and litho-biostratigraphic analysis

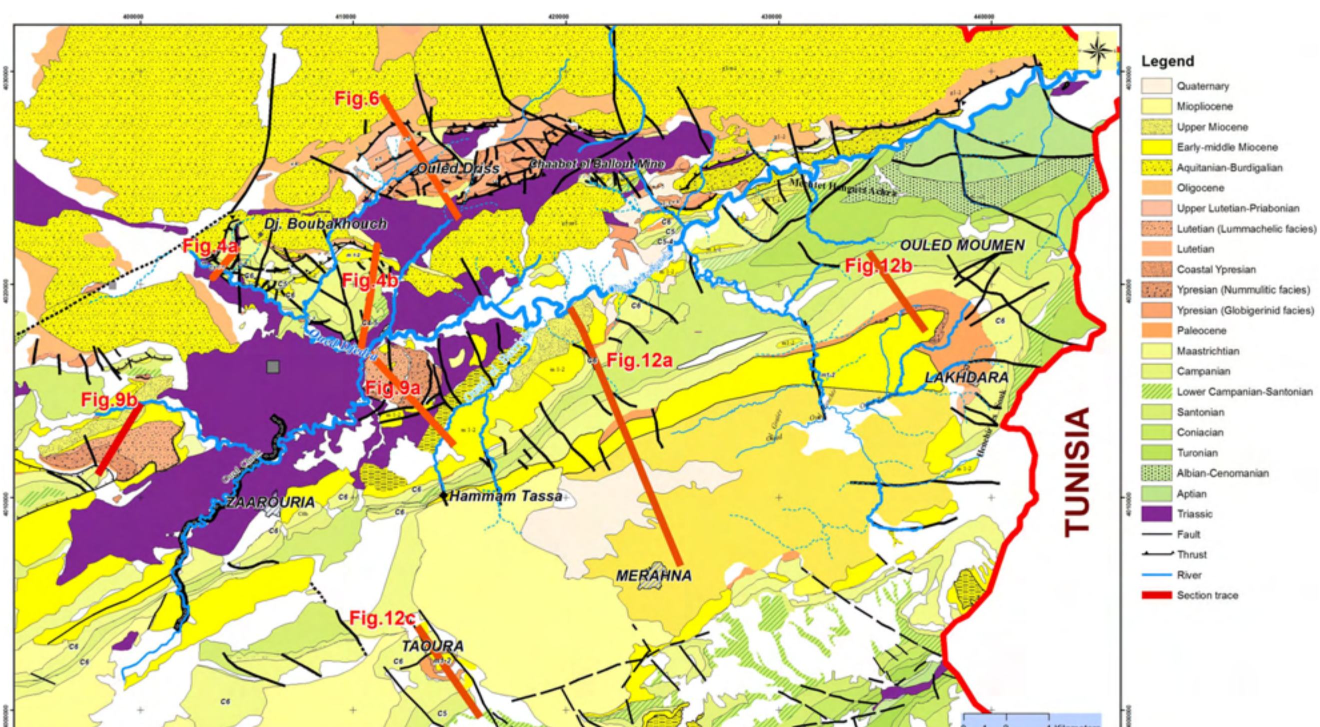


Fig. 3 Schematic geological map of study area showing biostratigraphic sampling and field based cross sections location.

Boubakhouch area

Djedra River section (Fig. 4a)

The section is NNE–SSW and has been measured at El Akiba River (tributary of Djedra River), between Dj. Tallal and Kef Labiod situated in the west part of Boubakhouch area (Fig. 3).

This section starts with clays packing decametric layer of gray to black limestone, very rich of gypsum and anhydrite belonging to the Souk Ahras Triassic material. Clays are rich in centimetric crystals of bipyramid Quartz and gypsum. There is a steep contact plunging northwestwards separating the Triassic formation from the underlying formations which are themselves deformed and presenting a large angle dipping to overturned.

Above comes a carbonate series of 120 m thick approximately of green to yellow mudstone- limestone and decimetric layers of gray mudstones series.

Sample Sp1 yielded a dominant planktonic foraminiferal association including *Dicarinella primitiva* (DALBIEZ), *Marginotruncana sinuosa* (PORTHAULT), *Marginotruncana marianosi* (DOUGLAS), *Dicarinella concavata* (BROTZEN) (infrequent), and few *Hedbergella* and *Marginotruncana schneegansi* (SIGAL). The presence of *Marginotruncana manaurensis*, indicates the upper Turonian. Benthic foraminifera are present but not numerous (*Lenticulina and Gyroidinoides subangulata*). More northwards, the section exhibits 150 m thick, of gray mudstones and yellowish limestone in decimetric beds ending with a 5m thick limestone bed. This bed is crosscut by a fault El Akiba River. Biostratigraphic analysis of Sp2 sample collected from this bed (Fig. 4a) yielded an abundant planktonic foraminifera association that defines Coniacian age including *Marginotruncana coronata* (BOLLI), *Marginotruncana sinuosa* (PORTHAULT), *Marginotruncana schneegansi* (SIGAL), and *Marginotruncana primitiva* (DABLIEZ), associated with benthic foraminifera such as (*Ammodiscus sp., Dorthia oxycona,* and *Trochammina sp.*).

More northwards, the section exhibits 200m-thick interval composed of an alternation of gray mudstones and limestone beds. The lower part of this interval (sample Sp3) is characterized by a rich planktonic foraminiferal assemblage such *Dicarinella concavata* (BROTZEN), *Hedbergella, Marginotruncana schneegansi* (SIGAL) indicating the Lower Santonian. Some Tens meters above, samples Sp4 and Sp5 biostratigraphic analysis indicates a dominant planktonic foraminiferal assemblage containing: *Dicarinella asymetrica* (SIGAL), *Globotruncanita elevata* (BROTZEN), *Globotruncanita stuartiformis* (DALBIEZ), *Globotruncana linneiana* (D'ORBIGNY), *Globotruncana lapparenti* (BROTZEN), *Globotruncana arca* (CSHMAN), *Contusotruncana fornicata* (PLUMMER), *Globotruncana bulloides* (VOGLER), *Heterohelix,* and *Hedbergella* characterizing the Late Santonian. Minor benthic foraminifera are represented by *Ammodiscus glabrata, Bermudezina danica, Tritaxia, Dorthia oxycona, Gyroidinoides subangulata, Neoflabellina delicatissima, Lenticulina,* and *Dorthia plummeri.*

Higher in the section, the interval consists in a 80–100m thick limestone bedset overlain gray mudstones, sample Sp6 yielded a very abundant planktonic foraminiferal assemblage

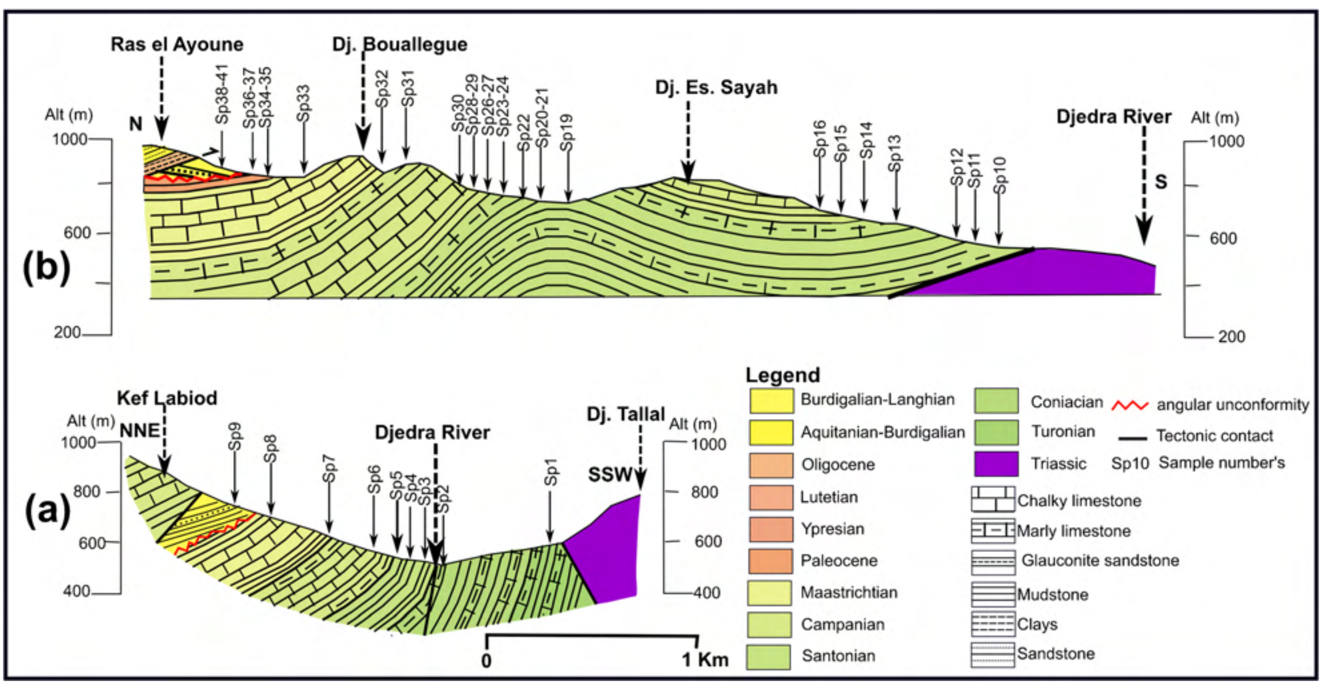


Fig. 4 Biostratigraphic cross sections showing samples and their location, **a** Djedra River section, **b** Dj. Es. Sayah section

including (*Contusotruncana fornicata* (PLUMMER), *Globotruncanita stuartiformis* (DABLIEZ), *Globotruncanita elevata* (BROTZEN), *Globotruncana arca* (CUSHMAN), *Globotruncana bulloides (*VOLGER), *Globotruncana linneiana* (D'OBIGNY), and *Heterohelix*), associated with benthic foraminifera assemblage (*Tritaxia, Lenticulina, Dorthia plummeri,* and *Frondicularis cf. frankei).* This assemblage characterizes the lower Campanian age. Northwards the section continues with three bedsets: The basal bedset is represented by more than 80m of gray mudstones-mudstone. From this bedset, the sample Sp7 mudstones delivers *Hedbergella, Heterohelix,* and *Globotruncanides*. The disappearance of *Globotruncanita elevata* (BROTZEN) indicates the early Maastrichtian. The median level exhibits a 100 m bar of yellow limestone with a whitish gray break in layers of 60 cm thick. The upper level shows a series of alternating decimetric beds of limestones and gray mudstones of about 60 m thick. Sample Sp8 taken from these mudstones provided abundant planktonic foraminiferal assemblage containing; Gansserina *gansseri* (BOLLI), *Contusotruncana contusa* (CUSHMAN), *Contusotruncana fornicata* (PLUMMER), *Globotruncanita stuartiformis* (DALBIEZ), *Globotrucanita angulata* (TILEV), *Globotrucanita subspinosa* (PESSAGNO), *Globotruncana ventricosa* (WHITE), *G. bulloides* (VOGLER), and *Abathomphalus mayaroensis* (BOLLI), characterizing late Maastrichtian. These mudstones also contain rare Ostracods (*Bairdia sp.* and *Cytherella sp.*). The Maastrichtian mudstones and limestone are overlaid by a detrital formation represented by brownish mudstones an sandstone rich in glauconitic mudstones and sandstone of about 160 m thickness. Sample Sp9 taken from mudstones layers, contains mineralized clasts, *Radiolaria*, calcite crystals, very abundant ferruginous concretions, reworked Globotruncana, and mineralized micro-faunas. The mudstones contain an assemblage of planktonic and benthic foraminifera assemblage. Planktonic foraminiferal assemblage is rich in Globigerinoides *trilobus* (REUSS), *Gl. quadrilobatus* (D'ORBIGNY), *Gl. bisphiricus* (TODD), and *Globoquadrina* which indicate the Burdigalian-Langhian age (Late - middle Miocene). Benthic foraminifera are represented by: *Ammodiscus glabrata, Trochammina,* abundant *Uvigerines Glomospira charoides,* and *Ammodiscoides.*

Djebel Es. Sayah section (Fig. 4b)

This section was measured in the eastern part of Boubakhouch area (North of Souk Ahras city), between Djedra River and Ras el Ayoune in the south of Ouled Driss city (Fig. 3). It allows documenting the Santonian to Paleocene Sellaoua foreland series and its Miocene overlaying. From South to North we can distinguish (Fig. 4b):

The Triassic formations (evaporites, yellowish, and greenish clays containing disturbed limestone beds) are overlain by a thick mudstones package including some mudstones-limestone and limestone beds. Samples (Sp10, Sp11, and Sp13) taken from the lower part of this column yielded an association rich in planktonic foraminiferal assemblage: *Dicarinella assymetrica* biozone including *Dicarinella concavata* (BROTZEN), *Dicarinella asymetrica* (SIGAL), *Globotruncana bulloides* (VOGLER), *Globotruncana arca* (CUSHMAN), *Globotruncana lapparenti* (BROTZEN), *Heterohelix, Hedbergella.* This assemblage is characterizing the Late Santonian- Early Campanian age. Benthic foraminifera also are present such as *Lenticulina, Tritaxia, Gaudryina pyramidina, Gaudryina inflata, Ammodiscus glabatra, Gyroidinoides subangulata,* and *Dorthia.* Upper wards in the series, samples (Sp14–Sp15) delivered a rich planktonic foraminiferal assemblage: *Globotruncanita elevata* (BROTZEN), *G. linneiana* (D'ORBIGNY), *G. arca* (CUSHMAN), *G. bulloides* (VOGLER), *Globotruncanita stuarti* (DE LAPPARENT), *Globotruncanita stuartiformis* (DALBIEZ), *Contusotruncana fornicata* (PLUMMER), and *Radotruncana calcarata* (CUSHMAN). This association dates the Early Campanian age. Sample Sp 16 contains *Globotruncana ventricosa* (WHITE) in addition to the mentioned species indicating the Middle Campanian age. The benthic foraminifera are present but scarce, including *Ammodiscus sp., Gaudryna inflata, Lenticulina, Bulimina, Dorthia,* and *Gyroidinoides subangulata*. On top of these mudstones, a chalky limestone bedset has been encountered, which is affected to Late Campanian age.

To the north, the Campanian bar is eroded and exposes the previous mudstones where Sp17 to Sp21 delivered an association rich in planktonic foraminiferal assemblage containing: *Dicarinella asymetrica* (SIGAL), *Marginotruncana sigali* (REICHEL), *Dicarinella concavata* (BROTZEN), *Globotruncana linneiana* (D'ORBIGNY), *Marginotruncana angusticarinata* (GANDOLFI) dating the Late Santonian age.

Samples Sp22 to Sp24 taken from the upper part of the mudstones have delivered *Hedbergella, Globotruncanita stuartiformis* (DABLIEZ), *Globotruncanita elevata* (BROTZEN), *Globotruncana arca* (CUSHMAN), *Globotruncana lapparenti* (BROTZEN), *Globotruncana bulloides* (VOGLER), and *Marginotruncana angusticarinata* (GANDOLFI). This association is characterizing the Early Campanian age.

Samples Sp25 to Sp29 delivered *Globotruncanita elevata* (BROTZEN), *Hedbergella, Globotruncanita stuartiformis* (DALBIEZ), *Globotruncana lapparenti* (BROTZEN), *Heterohelix, Globotruncana arca* (CUSHMAN), *Globotruncanita stuarti* (DE LAPPARENT), *Globotruncana ventricosa* (WHITE), *Globotruncana linneana* (D'ORBIGNY) dating the Middle Campanian age. Above Sp 30 taken below the limestone bar, delivered in addition *Radotruncana calcarata* (CUSHMAN), indicating the base of the Late Campanian age. The benthic foraminifera also are frequent and represented by *Cibicidoides, Bulimina, Uvigerina, Tritaxia, Neoflabellina delicatisima, Dorthia,* and *Lenticulina*. Higher in the series, appear a bar of 80m of chalky Inoceram-bearing limestone and ended with 10m of mudstones and limestone Late Campanian in age. This limestone bar is overlaid by an 80m-thick level of gray mudstones topped by chalky Inoceram-bearing limestone bar (100 m-thick). Sample Sp32, yielded an abundant planktonic foraminifera association including Globotruncanella havanensis (VOORWIJK) biozone dating Early Maastrichtian age. The limestone bar is topped by mudstones series where sample Sp33 is rich in planktonic foraminifera association comprising G. *Stuartiformis* (DABLIEZ), *Radotruncana subspinosa* (PESSAGNO), *G. gansseri* (BOLLI), *G. Falsostuarti* (SIGAL), *Globotruncanella havanensis* (VOORWIJK), *G. ventricosa* (WHITE) and *Abathomphalus mayaroensis* dating the Late Maastrichtian. Benthic foraminifera assemblage is present but less than planktonic foraminifera such *Dorthia plummeri, Nodosaria pauperculata, Tritaxia midwayensis, Ammodiscus,* and *Dorothia oxycona*. Ostracods also are present such as *Acanthocythereis meslei, Bairdia,* and *cytherella* sp.

The Cretaceous series are overlaid by gray to black mudstones where samples Sp34 and Sp35 show a radical change in planktonic foraminiferal assemblage. Where *Globotruncana, Hedbergella,* and *Heterohelix* extinguished definitively and appeared globigerinids. They delivered planktonic foraminifera association (*Globigerina triloculinoides G. daubjergensis* and rare *Planorotalites*), associated with benthic foraminifera assemblage (*Lenticulina, Nodosaria, Anommalina, Cibicidoides, and Nuttalites*) and ostracods (*Paleocosta makattamensis, Protobuntonia, Rachycythere*), characterizing the early Paleocene.

The Maastrichtian and Paleocene series are unconformably covered by detrital strata, represented by glauconitic mudstones and sandstones. Samples Sp36 and Sp37 yielded very rare uncharacteristic microfauna, samples Sp38–42 delivered planktonic foraminifera association characteristic of the Lower Langhian (Lower to Middle Miocene) represented by: *Praeorbulina glomerosa* (BLOW), *Praeorbulina transistoria* (BLOW), *Trilobatus trilobus* (REUSS), *Globigerinoides quadrilobatus primorduis* (BLOW & BANNER), *Globigerinoides altiaparturus,* and *globigerinoides bispherica* (TODD) (Fig. 5).

Ouled Driss area

Kef Echaam-Dj. Madjen section (Fig. 6)

This section is measured in the north-east of Dj. Boubakhouch in Ouled Driss sector (Fig. 3). The section exhibits a repetition of marls and limestone bars resting on top of the Ouled Driss Cretaceous and Triassic formations, and supporting the so called Numidian thrust sheet of Dj. Madjen-Dj. M'Cid. From bottom to top we can distinguish (Fig. 6): **Kef Echaam unit** (a): it exposes saliferous Triassic deposits surmounted by chalky limestone (10m thick) and gray marl (60m thick) in the base, black marl (180m thick) and gray-to-black limestone (140m) at the middle and black marl (300m) rich in yellow balls in the top.

Samples Sp42 and Sp42a taken from the gray mudstones above chalky limestone beds (Fig. 6), yielded a rich planktonic foraminiferal assemblage characterizing the Upper Maastrichtian biozone contain *Globotruncana stuarti* (DE LAPPARENT), *Globotrucanita stuartiformis* (DALBIEZ), *Globotruncana falsostuarti* (SIGAL), *Globotruncana aegyptiaca* (NKKADY), *Racemiguembilina fructicosa* (EGGER), *Gansserina gansseri* (BOLLI), and *Contusotruncana contusa* (CUSHMAN). We note the frequency of benthic foraminifera such as (*Ammodiscus, Lenticulina, Dorothia oxycona, Gyroidinoides subangulata, Cibicidoides, Uvegerina, Dentalina colei, Tritaxia,* and *Nodosaria*).

Upper, samples Sp43-Sp44 yielded benthic foraminifera association (*Lenticulina, Trochammina,* and *Ammodiscus*) associate with planktonic foraminiferal assemblage *Parasubbotina pseudobulloides* (PLUMER), *Globigerina triloculinoides* (PLUMER) characterizing the early Paleocene age (P1–P2).

- More upper, black marl series, are rich in organic matter and contain rare marl-limestone beds, biostratigraphic analysis indicates that samples Sp45 is rich in a diverse planktonic foraminiferal assemblage including; *Morozovella pseudobulloides, M. praecursoria, M. angulata, M. pusilla, Acarinina primitiva,* and *Planorotalites chapmani*. These species correspond to *Globigerina sellii* zone (P3 zone) of early to Middle Paleocene age.

A few tens meters higher, samples Sp46-Sp47 include *Globigerinoides triloculinoides, Planorotalites pseudomenardii, Morozovella velascoensis,* and *M. aequa*. These species correspond to *Planorotalites pseudomenardii* zone (P4 zone) of Late Paleocene age. Sample Sp48 contains in addition foraminifers of the previous levels: *Morozovella uncinata, M. velascoensis, M. conicotruncana,* and *Planorotalites pseudomenardii*. This level is attributed to *M. velascoensis* zone (P5) characterizing the Late Paleocene (Thanetian) age.

- The middle part (limestone bar) begins with an alternation of mar-limestone and marl beds. Samples Sp49 and Sp50 contain *M. aequa, Globigerina linaperta, M. subbotinae,* and *M. aragonensis*. This assemblage is attributed to *M. subbotinae* zone (P6–P7) characterizing the early Ypresian age. On this alternation a Globigerinous gray to black limestone bar exhibits decimetric beds rich in silex and phosphate.

Petrographic analysis supported by thin sections made from six (06) samples of rock taken from the different levels

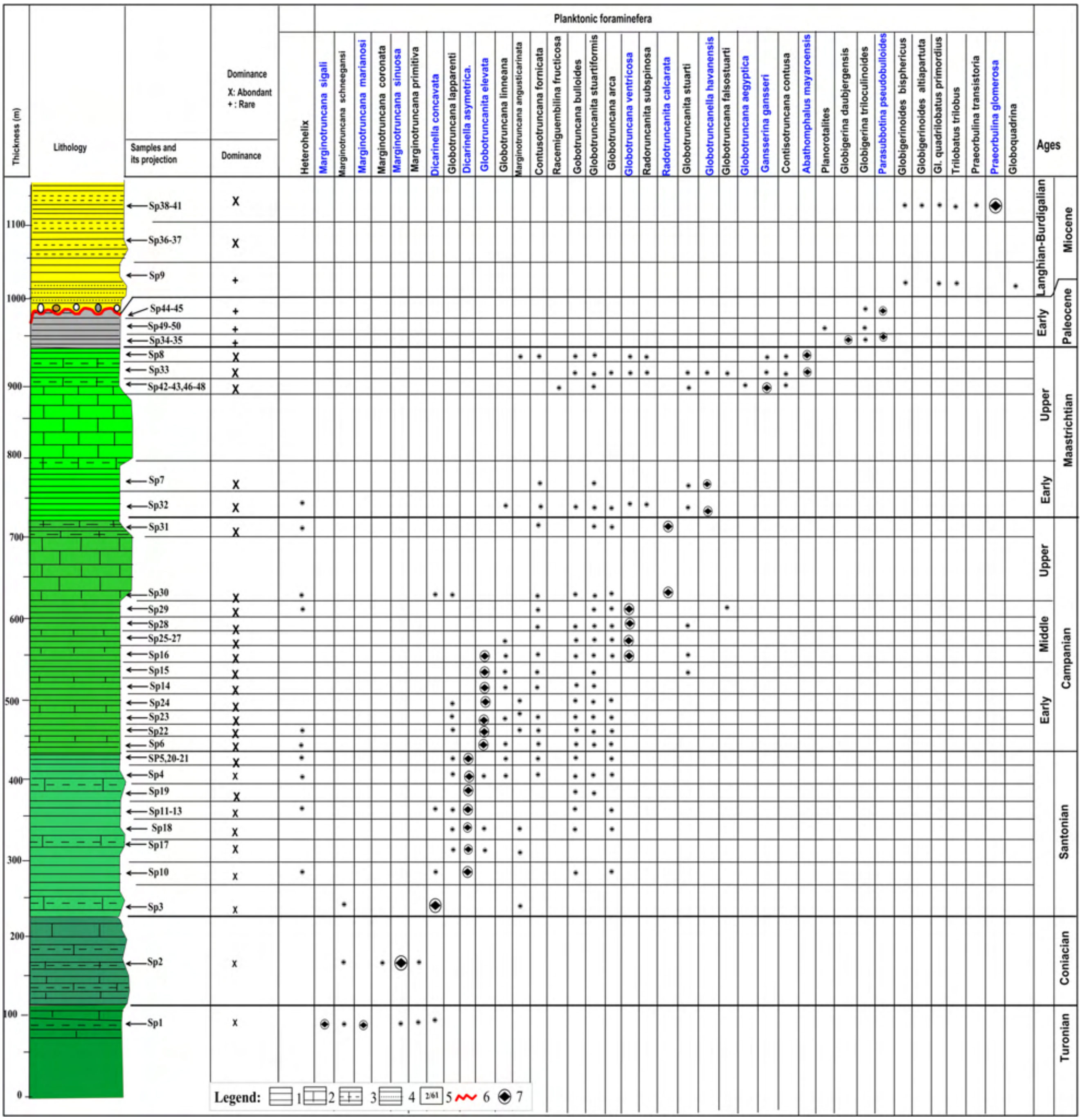


Fig. 5 Stratigraphic distribution chart of major planktonic foraminiferal species in Souk Ahras Sellaoua unit. Legend 1. Mudstones and clay, 2. Limestone, 3. Mudstones-limestone, 4.Sandstone, 5. Sample number, 6. Discontinuity, 7. Blow biozone

of this bar (Fig.7), shows a wakstone (biomicrite) rich in organic matter and planktonic foraminifera (*Globigerina* and *Morozovella*) and rare benthics (*Bolivina, bullimuna*), phosphatic clasts, and Ostracods debris. We note the presence of shark teethes (Fig. 7, Ts6) and coprolites.

- The upper part of the Dj. Hammam Tellian unit is characterized by a series (240 m thick) of black marl rich in yellow balls and containing a decimetric layer of sandstone at the base. Biostratigraphic analysis shows that Sp51 and Sp52 are free from microfossils, samples Sp53 contains plancktonic foraminiferal assemblages (*Morozovella subbotinae, M. aragonensis, and Acarinina bullbrooki*) associated with benthic foraminifera (*Lenticulina, bulimina, and Uvegerina*), outlining a Lutetian age.

Aïn Ghorab Tellian unit (b): above a tectonic contact, this unit starts with about ten (10m) meters of black marl where biostratigraphic analyzes indicate that sample Sp54 is rich in planktonic foraminiferal assemblages including

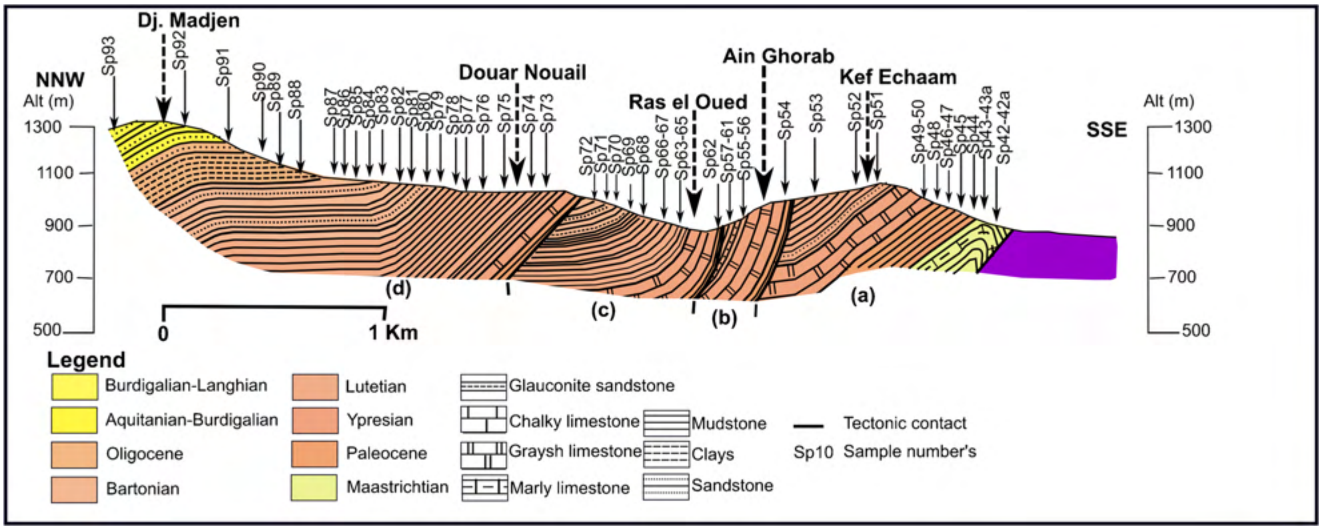


Fig. 6 Ouled Driss biostratigraphic cross section showing samples and their location

Globigerinoides triloculinoides, *Globigerina velascoensis, Planorothalites chapmani, Planorothalites pseudomenardii, Acarinina primitiva, Morozovella angulata, M. subbotinae, M. aequa, M. velascoensis,* and *M. acuta*. These species correspond to *M. velascoensis* zone (P5 zone) characterizing the Late Paleocene (Thanetian) age.

On these Paleocene (Thanetian) marls comes the Ypresian limestone bar (140m thick) similar to the Kef Echaam bar described previously. At the top of this bar the phosphatic and silex levels are well exposed.

Above this bar the black marl rich in yellow balls spreads out over approximately 120 m in thickness. The base of this level contains a decimetric sandstone bed. Samples taken from these marls (Sp55 and Sp56) include *Morozovella aragonensis, Acarinina pentacamerata, A. bullbrooki, and Globigerina inaequispira* associated with benthic foraminifera (*Lenticulina and Bolivina antegrissa*), outlining a Lutetian age. Samples Sp57–Sp61 contain only benthic foraminifera (*Lenticulina and Bolivina antegrissa*).

Ras El Oued Tellian unit (Fig. 4): this unit starts by Late Paleocene (Thanetian) marls were Sp62 livered (*Globigerinoides triloculinoides, Globigerina velascoensis, Planorothalites chapmani, P. pseudomenardii, Acarinina primitiva, Morozovella angulata, M. subbotinae, M. aequa, M. velascoensis,* and *M. acuta*) surmounted with Ypresian limestones (similar to in the previous unit), overlain by thick series of marl rich in yellow balls, but thicker than in the previous units and containing a glauconitic sandstone levels in the upper part (580m thick). Biostratigraphic analysis shows that samples Sp63–Sp65 contain only benthic foraminifera assemblages such *Bulimina* and *Bolivina antegrissa*. Samples Sp66 and Sp67 include *Globigerina linaperta*, associated with benthics (*Annomalina, Nonion, Bolivina antegrissa,* and *Uvegerina marginolopsis*). Few meters beneath the first glauconitic level, samples Sp68 and Sp69 contain *Acarinina bullbrooki, Globigerina eocaena,* and *Truncanorotaloides topilensis*. These assemblages provide a Late Lutetian age.

In the lower part of marl series which exhibit a glauconitic level, sample Sp70 displays a planktonic foraminiferal association comprising *Acarinina bullbrooki, Globigerina eocaena,* and *Turborotalia cerroazulensis*. The assemblage also identified in Sp71 and Sp72 samples is characterized by the presence of *Hantkenina alabamensis* outlining a *Bartonian* age. These marls are rich in benthic foraminifera assemblage such *Lenticulina, Bulimina, Bolivina antegrissa,* and *Uvegerina marginolopsis*.

Douar Nouail –M'cid Tellian unit (Fig. 4): this section begins with Thanetian marls which are overlain by the Ypresian limestone bar, which is only 30 meters thick here. At the base of the black marl rich in yellow balls (360 m thick), sample Sp73 provided *Morozovella subbotinae, Acarinina broedermanni, and Globigerina inaequispira,* thus dating the early Lutetian. Benthic foraminifera such *Lenticulina, Bulimina, Bolivina antegrissa,* and *Uvegerina marginolopsis* are also present. Samples Sp74–Sp79 contain planktonic foraminiferal assemblages dating the Lutetian. The planktonic foraminiferal assemblages defined from samples Sp80–Sp84 collected from the base of the glauconitic level are characterized by the presence of *Acarinina bullbrooki, Globigerina eocaena, Turborotalia cerroazulensis, Truncanorotaloides topilensis, T. libyaensis, Hantkenina demblei,* and *Globigerinatheka suconglobata* dating the Bartonian age. In the uppermost part, samples Sp85–87, contain *Truncanorotaloides hayanensis* and *Glaubigerinatheka Mexicana*, indicating a Bartonian-Priabonian age. We note that the Bartonian to Priabonian series is 220 m thick and rich in benthic foraminifers' assemblages. Upwards comes a detrital series called the Numidian thrust sheet, it began with 120 m thick of greenish clay with centimetric levels of fine sandstone

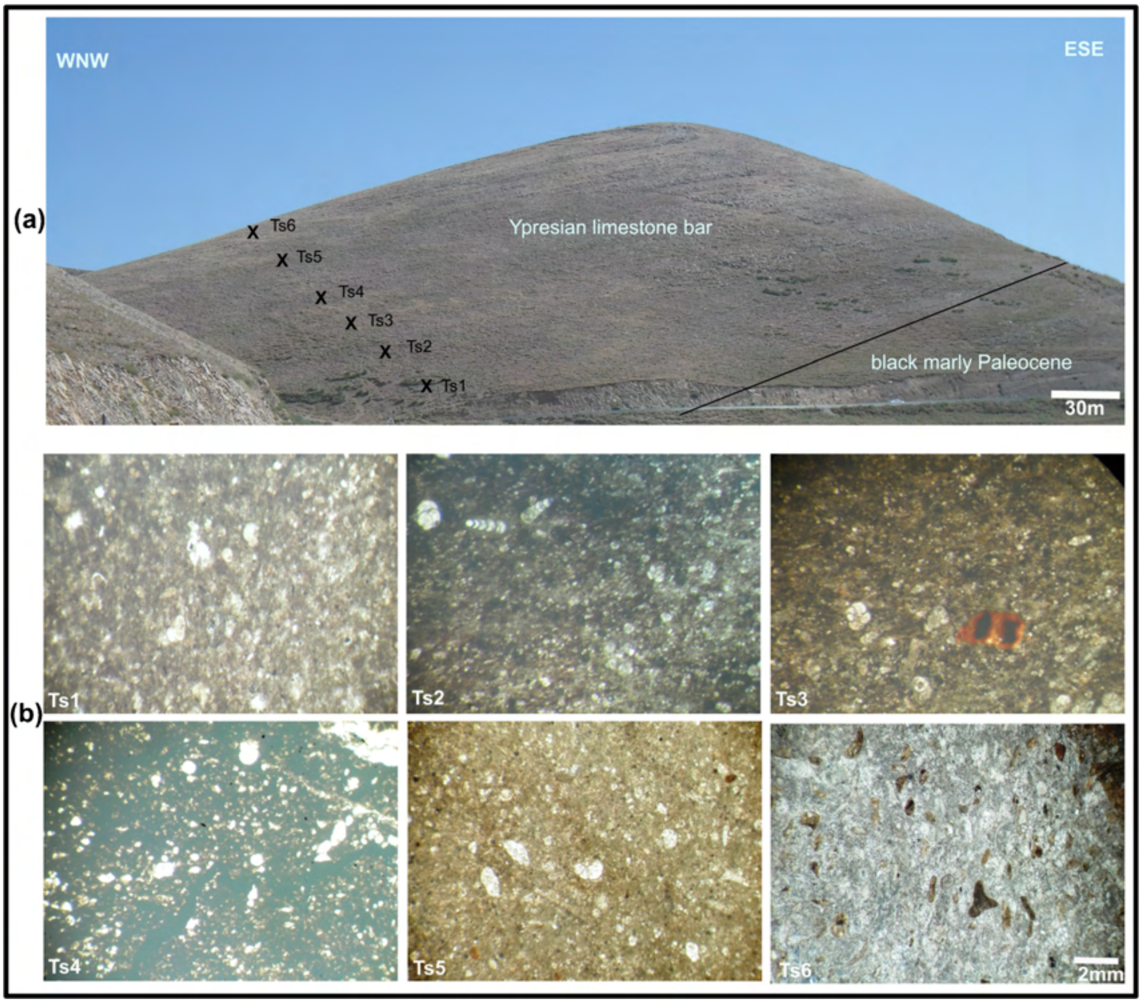


Fig. 7 Ypresian limestone bar showing **a** thin sections positions **b** thin sections in microscopic view. Legend: Thin section1 (Ts1) Wackestone: biomicrite including pyrite pigment, rich in Morozovelles, Globigerines and organic matter, Ts2, and Ts3 Wackestone: biomicrite containing Morozovella, Globigerina species and radiolarians, rich in organic matter, Ts4 Wackestone: biomicrite rich in organic matter, planktonic foraminifera and rare Bolivina, Ts5 Wackestone: Phosphatic biomicrite containing species of Globigerina, Bolivina, Bulimina and radiolarians, Ts6 Wackestone: biomicrite very rich in phosphates, phosphatic clasts, ostracods debris. Only Globigerines species are present with some shark teethes and coprolites

and continues upwards with an alternating of sandy mudstone and sandstone bars (> 800m thick) containing micro-conglomerate levels of quartzite pebbles. The samples collected from the base of clay series are free of microfossils, upper in the series samples Sp88 and Sp89 livered an agglutinate microfossils represented by *Globigerina ciperolusis*, *Globigerina tauriensis* and *Globigerina tripartita*, dating the Oligocene age (P20). Samples collected from the alternating zone are free of microfossils. This series is dated in the north and the west of the study area and affected to the Aquitanian-Burdigalian age (Lahondère et al. 1979; Vila 1980). Biostraphic results are synthesized in the Fig. 8

Boukebch and Dekma area

This sector is situated in the south of Boubakhouch and Ouled Driss sectors (Fig. 3). It includes the outcrops of Dj. Boukebch in the east and Dj. Dekma in the west. The outcrops of this sector are been well studied by Blayac (1902 and 1912), David (1956). In the present study, we covered some gaps in relation to the petrography and the structure. The Eocene outcrops of this sector are rich in nummulites, bivales, gastropods, and oysters. Field observations are synthesized by the Boukebch and Dekma sections (Fig. 8).

Boukebch section (Fig. 9a)

The Boukebch section is measured between Dj. Ouled Soltane in the south and Madjerda River in the north oriented ESE–WNW. From the ESE to WNW, it exhibits:

- Campanian- Paleocene Carbonate series (gray marl and chalky limestone bars in the Campanian-Maastrichtian and blackish marl in Paleocene period) unconformably overlies by Burdigalian–Serravallian detrital series (brownish

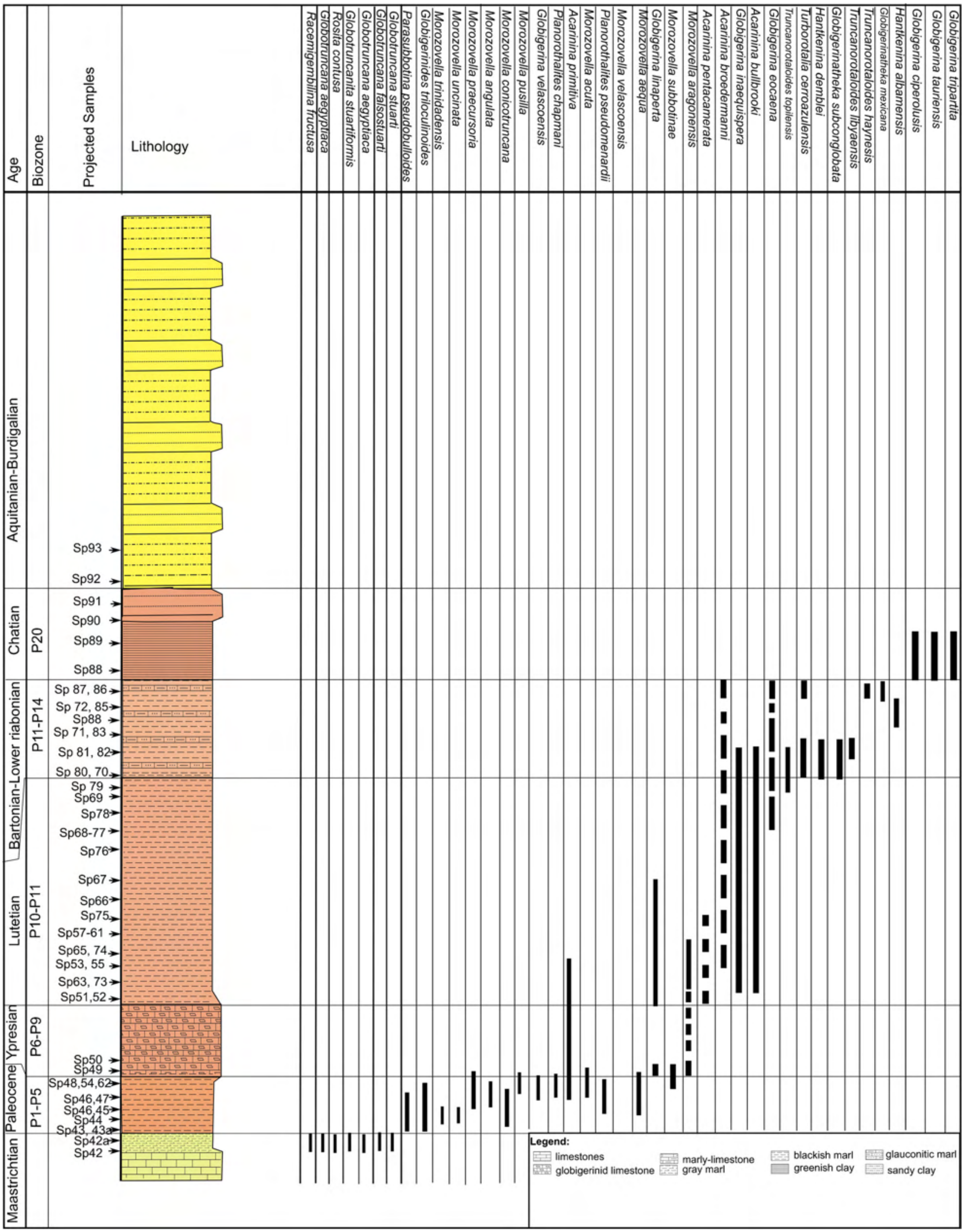


Fig. 8 Stratigraphic distribution chart of major planktonic foraminiferal species in Souk Ahras Sellaoua Foreland series

mudstone, glauconite, and glauconitic sandstone). Sample Sp 94 does not contain characteristic micro-fauna; we attributed it to the Serravallian age by facies analogy with that of northern Tunisian Miocene (Pr. Ben Ismail). The Miocene series are thicker than 800m.

- Triassic material thrusts the Miocene series; it is represented with gypsum, anhydrite, argillites, and dolomite.

- Boukebch nummulitic Tellian unit which is in tectonic contact with Triassic bodies, it exposes black marl in the base. Biostratigraphic analysis of sample (Sp95) taken from this marl provided a rich benthic foraminifera assemblage (*Tritaxia midwayensis, Ammodiscus glabrata, Trochammina abrupta,* and *Trochamina budashvaella)* indicating a Paleocene age. On top of these marls a thick nummulitic limestone bar develops and is subdivided as follows from bottom to top (Fig. 9): 20m thick of limestone formed only of nummulitids accumulation (Fig. 10a) surmounted by 40m thick of red massif limestone very rich in large nummulitids (Fig. 10b), overlain by 20m thick of brown limestone rich in nummulitids, lumachelles, and bivalves (Fig. 10c). Thin sections Ts1–Ts3 taken from these levels (Fig. 9a) show a nummulitic pakstones (Fig. 11a, 11b). These layers are dated as Ypresian in age by David (1956).

The limestone bar grades upwards into white limestone (40 m thick) rich in large Nummulites (Fig. 10e) such as (*Nummulite irregularis, N. subirregularis, N. globulus, N. atacicus, N. subatacicus,* and *N. gizehensis),* dating the Late Lutetian age (David 1956).

The nummulitic limestone bar is covered by brownish sandy and marl series (180 m thick) containing some fossiliferous limestone beds (3 – 5 m thick) in the middle and fragmented bioclastic limestone beds at the top (Figs. 10d, 10e, 11d). Marl levels are rich in gastropods (*Phasianella sp.)* Fig.10f. Biostratigraphic analysis of samples (Sp96 and Sp97) taken from these marls provided *Lenticulines,* rare *Morozovelles, Globigerines,* and Ostracods (*Loculocyteretta*) dating the Lutetian age. The fossiliferous limestone beds in the middle of marl series are rich in gastropods (*Turritella carinifera, Phasianella sp.*), lumachelle, and clams (Fig. 10d, 10e).

- On top, Miocene series formed by brownish marl and glauconitic and fossiliferous sandstone and sandstone reshaping centimetric balls of Nummulitids (Figs. 10g, 10h, 11e, and 11f), conglomerate being mostly eroded and preserved in only small outcrops resting directly on top of the Lutetian and Triassic series.

Dekma section (Fig. 9b)

This section is measured between Dj. Serrou in the south and Madjerda River in the north oriented SW–NE direction (Fig. 9b). It exhibits Santonian-Maastrichtian carbonate series (gray marl in the base and tow chalky limestones bars Inocerams-bearing), similar than described in Dj. Es. Sayah section, without any apparent change. On the Cretaceous series, comes the Paleocene black marls which cover them without any observable discontinuity; the upper Maastrichtian alternation of marl and limestone levels is progressively impoverished in limestone level and increasingly become black marl.

Upper, the Ypresian-Late Lutetian period exhibits a nummulitic limestone bar similar than of Boukebch section, but nummulites are not well developed. While the Lutetian series are well exhibited and richer in Oysters and gastropods fossils in Dekma section. It shows from the base to the top the following succession:

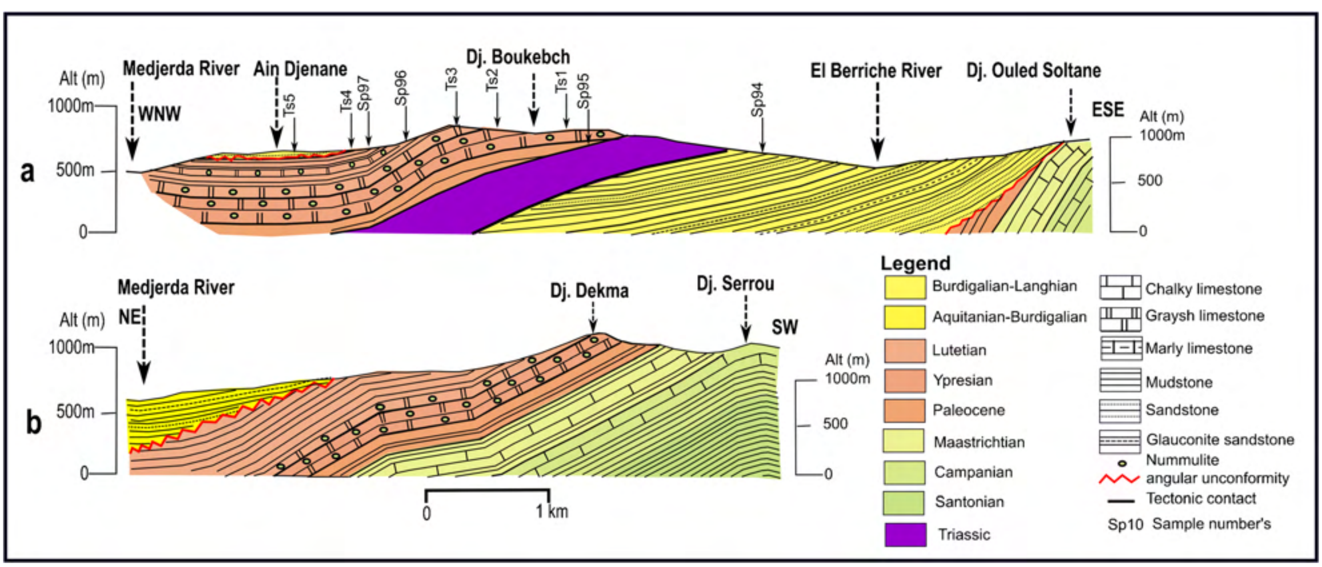


Fig. 9 Boukebch and Dekma biostratigraphic cross sections showing samples and their location **a** Boukebch section, **b** Dekma section

Fig. 10 Boukebch Nummulitids macro-facies and its Miocene photographs. Legend: **a** Nummulitic limestone (level 1), **b** large nummulitic red limestone (level 2), **c, d** white limestone rich in mollusk, bivalves and Turritelles, **d** *Turritella carinifera*, **e** fossiliferous limestone **f** *Phasianella sp*, **g** fossiliferous Miocene sandstone, Miocene conglomerate reshaping Nummulitids balls

- 10 m thick of gray sandy mudstone and sandy limestone large nummulites bearing, containing phosphatic, gastropods levels, and fossils debris.
- 60–80m thick of Gray marls and marls with gray limestone levels rich in oysters and silicified detrital limestones.
- 50–60m thick of gray mudstone containing Oysters limestone, decimetric levels of limestones rich in fragments of marine fossil shells.
- 20m thick of glauconitic limestone and glauconite rich in fragments of oyster and mollusk shells.

On top, the Burdigalian- Langhian siliciclastic material is unconformably on the Lutetian series. Miocene series starts above a gully level with a ferruginous level and continues upwards with brownish marl and sandstones (late Burdigalian-Langhian) in age and late Miocene series, similar to the Neogene series exposed in underlaing thrust sheets farther to the south (Miocene of Berriche River syncline). Notice that Dekma Miocene series are better conserved than the Boukebch Miocene series, the later being mostly eroded and preserved in only small outcrops resting directly on top of the Lutetian series.

Dj. Graout area

Graout are is part of Medjerda High domain and situated in the southeast of Boukebch- Dekma sector (Figs. 2 and 3). Three NNW–SSE sections are measured in this area (Fig. 12).

The main section is measured between O. Berriche and Merahna city (14 km long). It exhibits Senonian-Miocene series (Fig. 12a). The section exhibits gray marly dominant

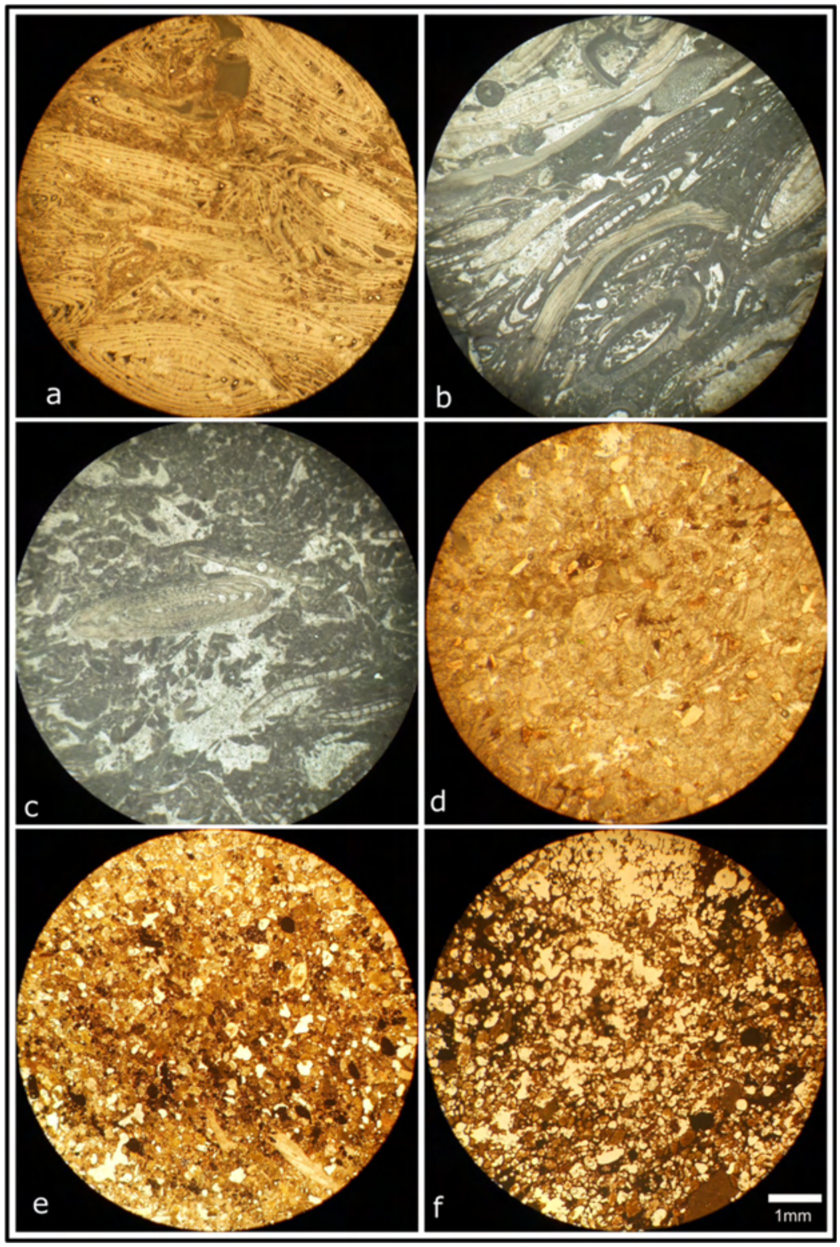


Fig. 11 Boukebch Nummulitids micro-facies. Legend: **a, b, and c** Nummulitid pakstone microfacies (Ts1, Ts2, Ts3), **d** fragmented bioclastic limestone, **e** and **f** Miocene fossiliferous and glauconitic sandstone)

which constitute the heart of Graout anticline, chalky micritic limestone rich in inocerams organized in tow bars form Graout anticline limbs. Limestones bars are separated and topped by gray marly series. Biostratigraphic analysis indicates that Sp98 is rich of planktonic assemblage and ostracods characterizing the upper Santonian age: Planktonic foraminiferal: *Globotruncana sigalia,* Frequent *Dicarinella assymetrica*, *Globotruncana stuartiformis*. Ostracods are represented by *Acanthocytheries meslei, Spiroleberis megiddoensis, Haughtoni leberisaciès*.

Samples Sp99 and Sp100 delivered *Globotruncana stuartiformis, G. elevata, G. linneiana, Rosita fornicata, G. arca* and some species of *Dicarinella assymetrica*, rare benthics (*Vaginolopsis, Dorothia, Gyroidinoides, Spiroplectammina*), and ostracods (*Actinocytheries coronata*) indicating the Santonian–Campanian age. Sp101 taken from marls in the base of the second chalky limestone bar delivered exclusively planktonic foraminiferal assemblage represented by *Globotruncana stuartiformis, Globotruncana arca, G. havaensis, G. angulata, G. falsostuarti, G. gansseri,* and *G. contusa* dating the middle Maastrichtian age.

Upper samples Sp102–Sp105 taken from the marls on top the second chalky limestone bare livered mixed association of planktonic and benthic foraminifera assemblage and ostracods dating the upper Maastrichtian. Planktonic foraminiferal are: *Globotruncanita falsostuarti, Rosita contusa, Globotruncanita stuartiformis,* and *Gansserina gansseri.*

On upper Maastrichtian gray marl develops 160–240m thick of black marl rich in organic matter, samples Sp106–

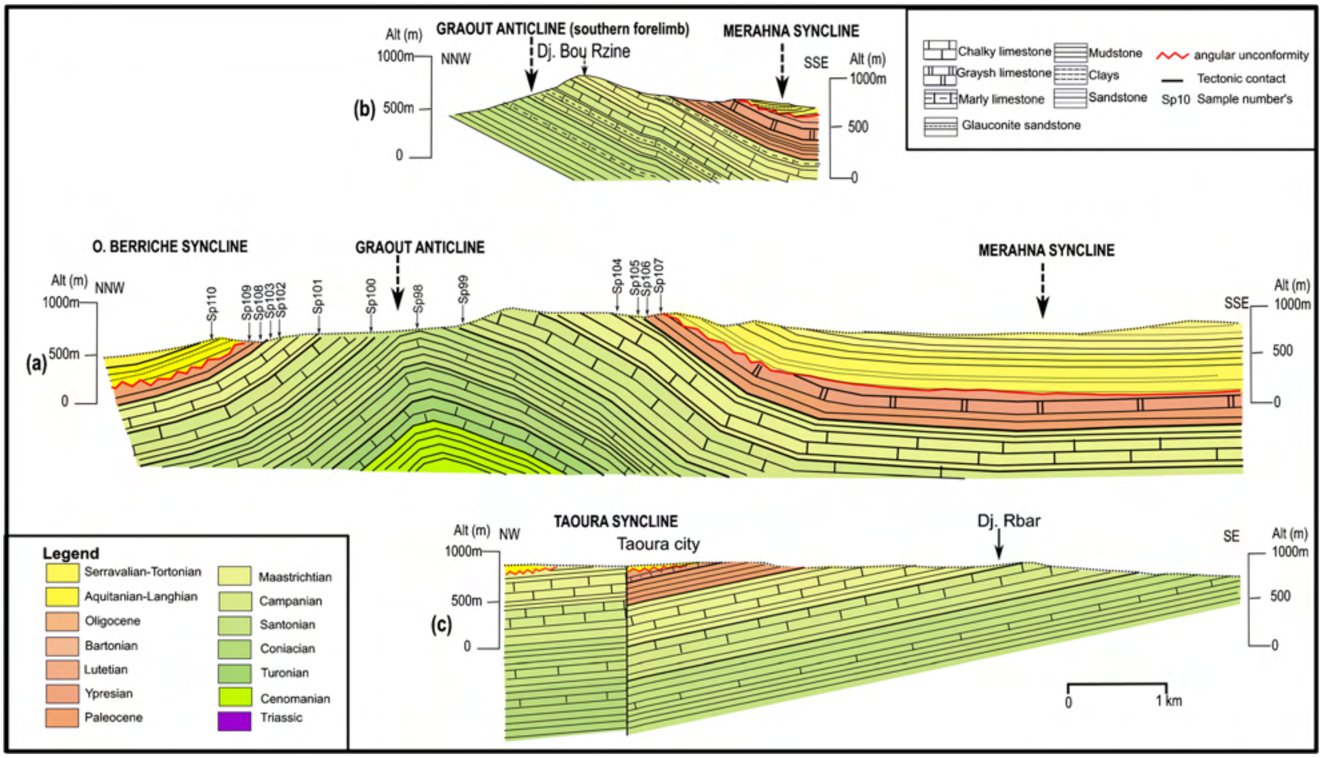
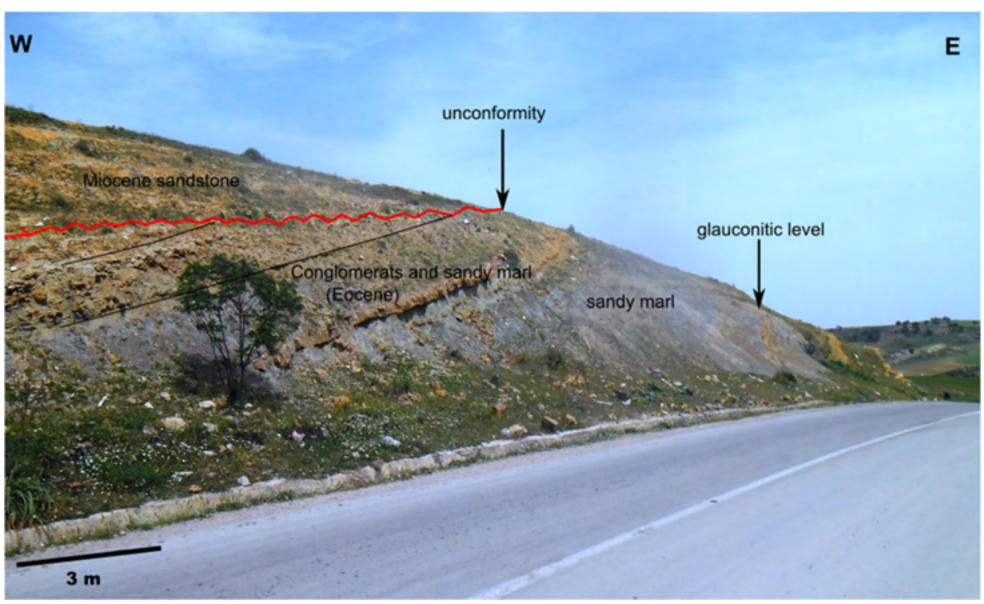


Fig. 12 Medjerda High sections **a** Oued Berriche – Merahna section, **b** Dj. Bourzine section showing Miocene series unconformably covering Ypresian limestone with rare small Nummulitids, **c** Taoura section showing Miocene series unconformably covering littoral Eocene facies

Sp109 delivered foraminiferal association dominated by planktonic foraminiferal association (*Globigerina daubgeyensis, G. trinidanensis, G. triloculinoides* et *Morozovella pseudobulloides)* benthic foraminifera are represented by *(Bulimina, Bolivina, Gyroidinoides subangulata, Cibicidoides,* and *Dentalina*). These assemblage dates the Paleocene age. The Tertiary-Cretaceous passage is concordant and the Paleocene age is identified by the change of microfauna.

Eastward, South of Dj. Bourzine (Fig. 9b) marl Paleocene are overlies by 45m thick of limestones bar containing infrequent small Nummulitids Ypresian-Lutetian age (David 1956). Westwards at Taoura city (Fig. 9c), marl Paleocene are overlies by 10–20 m thick of sandy-marls, glauconite,

Fig. 13 Photograph of Taoura Eocene series unconformably overlies by Miocene sandstone



conglomerate, and yellow micro breccias-limestone. We note the presence of decimetric phosphatic level (Fig. 13).

Finally comes Miocene series (Fig. 14h) represented alternating of sandstone – mudstone and glauconite of lower Miocene (Kriviakine et al. 1989a) (> 400m thick), gray to brownish mudstone with some centimetric to decimetric fine sandstone levels of middle Miocene (Kriviakine et al. 1989a) and medium yellowish sandstones which evolve upwards into conglomerates containing indiscriminate fossil shells (400–500m thick). The top of series contains clays containing metric lenses of gypsum and resedimented limestone blocks. This series is about 250 m thick and affected to upper Miocene (Kriviakine et al. 1989a). We note that Taoura Miocene series are only sandstone containing centimetric grains of quartz.

Between Merahna and Taoura cities (Fig. 3) develops a continental series formed of red clays, sandstones, sandy, conglomerate, and breccias material unconformably cover the Miocene series and affected to Pliocene age (David 1956).

Stratigraphic succession of Souk Ahras basin (Fig. 14)

The stratigraphic succession of Souk Ahras basin is produced from the geological maps covering the basin, the PhD reports carried out in the region and the our own field work.

Figure 14 shows a stratigraphic correlation between the mains area stratigraphic columns. The oldest age described is the Aptian, considering that Triassic material is not in its stratigraphic place.

Triassic

Triassic material outcrops in numerous locations, from north to south we can distinguish: Nador – Machrouha outcrop in the NW of study area, in Ras el Alia and Tifeche areas and in Souk Ahras area (Fig. 2). These Triassic occurrences are involved within Turonian to Maastrichtian and with Burdigalian-Langhian (middle Miocene) strata. The Triassic facies is represented by a Germanic facies; it consists of a chaotic mixture of gypsum, clay, silt, anhydrite, limestone, dolomite, and sandstone. We emphasize that the halite, which is often dissolved at the surface, is known only on subsurface, in Ouenza region (to the South of studied area).

Jurassic

Jurassic outcrops are very scarce; it was characterized only in Aïn Achour to the north of Hammam N'Bail city (in the northwest of study area). It is composed by a massive dolomitic limestone and unconformably covered by post orogenic deposits of Hammam N'Bail basin. This site is studied by (David 1956; Vila 1980; Chouabbi 1987; Peybernès et al. 2002) and is attributed to lower-middle Lias age. Jurassic pebbles are present in Mio-Pliocene series (Chouabbi 1987; Peybernès et al. 2002). Micro-palaeontological study of these pebbles attests the occurrence in the substratum of the Sellaoua foreland basin of a Jurassic–Berriasian carbonate-dominated series belonging to the Mesozoic southern tethyan platform as known in Northern Algerian and Tunisian Atlases (Peybernès et al. 2002).

Lower cretaceous

Neocomian pebbles are present in the Mio-Pliocene series (Chouabbi 1987; Peybernès et al. 2002). The middle-late Beriasian are evidenced by Calpionella occurrences.

- Barremian deposits outcrop in the south of Hammam N'Bail city; they are represented by thin layer of sandstone at the base topped by varicolored mudstones and pink mudstones limestone and sandstone (Chouabbi 1987).
- Aptian constitutes the core of Graout anticline between Sidi Lehmissi and Oued Mougras station. It is mainly composed of dark marls, limestones, and sandstones (Kriviakine et al. 1989a, b, c).
- Albian – Cenomanian outcrop in Graout anticline and constitute a 700m thick package of blackish gray marl sparsely interbedded by decimetric intercalations of black limestones. Kuscer and Dozet, (1972) encountered in the upper part of this complex: Planomalina buxtorfi (Gandolfi), Ticinella multiloculata (Morrow) and Hedbergella sp., Hedbergila portsdownensis (Williams et Mitchell), (Globigerinids) sp., and Rotalipora cushmani cushmani (Morrow).

Upper cretaceous

- Vraconian – Cenomanian: The Albian-Cenomanian series are represented in Hammam N'Bail area and are characterized by the presence of chalky limestones covered by mudstones and white mudstones limestone of Cenomanian age (Chouabbi 1987).
- Turonian is the oldest documented age in Souk Ahras region. It is cropping out in Oued el Akiba (West of Dj. Boubakhouch) and in the northeast part of Grout anticline. It is one hundred fifty meters (150 m) thick of yellowish limestone (beds of 30 to 40cm) alternating with gray mudstones. It is defined by a rich association of planktonic foraminifera *Marginotruncana manaurensis* (GANDOLFI), *Dicarinella primitiva* (DALBIEZ), *Marginotruncana sinuosa* (PORTHAULT), and *Dicarinella concavata* (BROTZEN) with the presence of infrequent benthic foraminifera. In the Hammam N'Bail area the thickness of Turonian is 100–120m (Vila 1980).

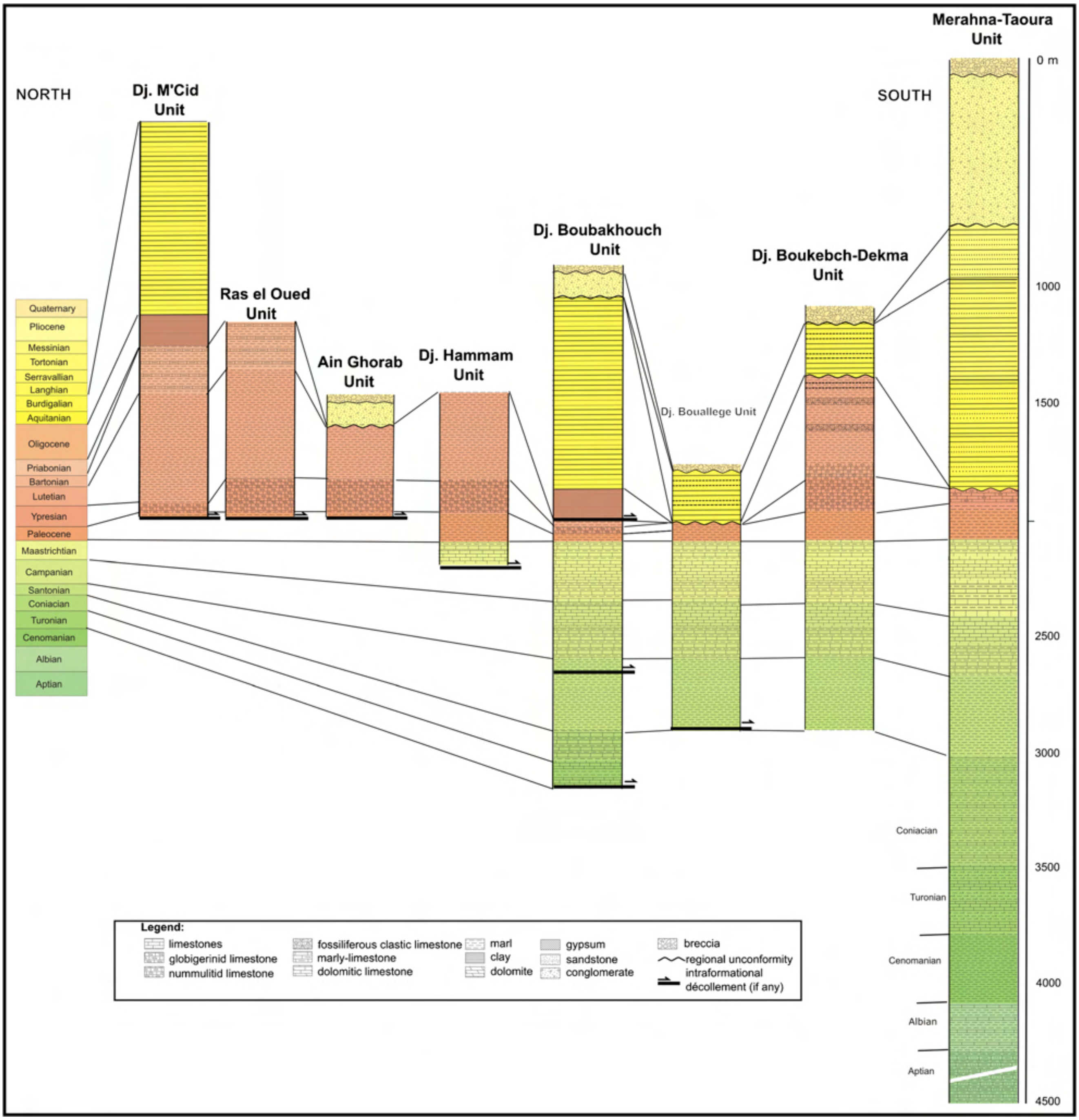


Fig. 14 Stratigraphic correlation between Souk Ahras main units. Intraformational decollement have been located

- Coniacian is outcropping at Oued Akiba and Graout anticline; it is represented by 120 m thick of gray mudstones and limestone containing only planktonic foraminiferal association of the *Marginotruncana Sinuosa* biozone. They include *Marginotruncana coronata* (BOLLI), *Marginotruncana Schneegansi* (SIGAL), and *Marginotruncana primitiva* (DALBIEZ).
- Santonian outcrops in Dj. Boubakhouch and in the left border of Medjerda River between Mechtat Barrache and in Serrou and Graout anticlines. It is dominated by gray mudstones, with rare decimetric levels of mudstones-limestone. It is about 200 – 300 m thick (Fig. 13) and is characterized by rich planktonic foraminiferal assemblage of *Dicarinella concavata* (BROTZEN) and *D. asymetrica* (SIGAL) biozone associated to a benthic foraminifera and Ostracods.
- Campanian it is 250 m to 380 m thick, and characterized by 100 m thick package of grayish mudstones in the base

containing abundant planktonic foraminiferal assemblage including a significant taxa, (*Globotruncanita elevata*). The middle and upper Campanian are represented by 80 m alternating mudstones and mudstone-calcareous surmounted by a bar of 80 m to 100 m thick of chalky limestone containing inocerams and ended with 10m of alternating mudstones-limestone. The planktonic foraminifera contained in these series belong to *Globotruncana ventricosa* (WHITE) and *G. calcarata* (CUSHMAN) biozone. The benthic foraminifera and ostracods exist but are not dominant.

- Maastrichtian the outcrops are characterized by three packages; the lower is 80 to 200 m thick of gray mudstones series of Early Maastrichtian age evidenced by planktonic foraminifera of a significant taxa *Globotruncanella havanensis* (VOORWIJK). The middle and the upper packages are upper Maastrichtian in age, they are represented by a bar of chalky white limestone (Fig. 7) with inocerams (100 m thickness) topped by an alternation of limestones and gray mudstones (60 m) (Fig. 13). These stratigraphic units are rich in planktonic foraminifers such as: *Globotruncana aegyptiaca* (NAKKADY), *Gansserina gansseri* (BOLLI), and *Abathomphalus Mayaroensis* (BOLLI) biozone. The benthic foraminifera and Ostracods are diversified but less dominant than planktonic (Figs. 5, 6). In the west of the study area in Lahnancha region the Maastrichtian series are thicker in Boubakhouch sector and reaches 380 m thick.

Paleocene

The Cretaceous - Paleogene boundary is defined by the occurrence of a series of about 160–200 m thick of dark gray mudstones layer rich in organic matter (Fig. 13). The occurrence of planktonic foraminifera of the early Paleocene, *Parasubbotina pseudobulloides* (PLUMMER) biozone, *Globigerina triloculinoides* (PLUMMER), *Globigerina daujergensis* (BRONNIMANN), and rare Planorotalites indicates the lower Paleocene.

Eocene

The Eocene is composed by three lithofaciès: Globigirenid facies in the north (Boubekouch and Ouled Driss sectors), Nummulitid facies in Boukebch Dekma sectors and near shore facies in the southern sector (Taoura) with a lateral shift of facies east of Merahna-Taoura syncline.

- Northern facies, outcrops in Ouled Driss, Boubakhouch, and Klaiaiya areas are characterized by a globigerinids facies. It exhibits a 140m thick of Ypresian limestone bar rich in silex and phosphatic level, 500m thick of Lutetian gray to black marl with yellow balls and 220m thick of Bartonian-Priabonian glauconitic marl and sandstone. We note that the benthic foraminiferal becoming more and more dominant from Lutetian to Priabonian period.
- The central facies outcrops in Boukebch and Dekma areas and is dominated by a Nummulitid facies. It shows 320m thick of Ypresian-Lutetian Nummulitid and lumachillic limestone bar and marlstone.
- Southern facies, crops in Taoura area, it exhibits a near shore facies characterized by sandy marl, breccias limestones, and conglomerates.

Oligocene

The Oligocene sequence is recognized under the Numidian Miocene mudstones. It is constituted by a 140m thick of green glauconitic clays containing centimetric beds of fine-grained quartzitic sandstone, dated with an agglutinate planktonic foraminiferal assemblage. It is unconformably overlying Eocene bars.

Miocene

We distinguish three facies from north to south:

- A turbiditic facies so-called Numidian sandstone, with very thick series (>1000m thick) of alternating sandy clays and sandstone (20–50m of sandy clay with 10-30m of sandstone containing conglomeratic slump), Aquitanian-Burdigalian in age very poor in fauna and micro-fauna. This facies is well developed on top of Tellian facies (globigerinids facies),
- In the Sellaoua foreland, Burdigalian to Langhian deposit are made of conglomerates, sandstones, brownish marl and glauconitic clay. The thickness is about 500 m.
- Southward in the Medjerda High, the Miocene is deposited above a regional unconformity (Fig. 3). Such unconformity is characterized by incision of paleovalley. The filling sequence is based by littoral sandstones and brownish marl of Aquitanian to Burdigalian age, contains the marly Serravallian-Tortonian and is achieved by evaporitic strata of the Messinian(?).

Plio-quaternary

The series of this period was called (postnappe series), they are unconformably overlies all the previous series and are formed by conglomerate, sandstone, and clays. In some places, they form huge deposits exceeding 1200m thick.

Structural results

In the study area four potential decollements are recognized and correspond to mudstones and clay. The lower is located in Triassic evaporites. It is inferred as the Triassic occurrences are evidenced as halokinetic bodies imbedded in the Cretaceous stratigraphic pile. The second decollement is observed at the Santonian-Campanian boundary, where mudstones are at the base of a competent limestone package. The third is in the mudstones of lower Maastrichtian. The fourth is located in Paleocene black shales under the Ypresian limestone bar.

As in worldwide fold-and-thrust belts (Poblet and Lisle 2011), the Souk Ahras foreland structure must be considered as an interference of inversion of pre-shortening geometries, mechanical stratigraphy and thrust tectonics. Our stratigraphic reappraisal of the Souk Ahras foreland allows defining its structural architecture (Figs. 15 and 16).

This structural architecture consists of two domains. The northern domain is dominated by thin-skinned thrust tectonics and its geometry can be explained by a duplex thrust systems. Based on field surveys and in absence of subsurface data the floor thrust can be located at the top of the lower Cretaceous massive limestones and the roof thrust within the Santonian-Turonian black shale. Imbricates sole out on this upper detachment forming the so-called Tellian Nappes including, if any, the Numidian Nappe. In the footwall of the Djebel Boubakhouch syncline, the Sellaoua Unit is folded by SSE verging thrust-related anticline. The thrust sequence is break-forward as evidenced by the Boukech klippe in the frontal limb of the Bouallegue anticline. Triassic remnants (Ouled Driss Triassic) are involved in this thrust-wedge and constitute signatures of pre- or early contractional salt tectonics.

The southern domain is dominated by thick-skinned tectonics and corresponds to the Medjerda High. In this domain, the Graout anticlines and the Lakhadara-Taoura syncline are large folds involving the whole Mesozoic stratigraphic pile and probably the Triassic in its stratigraphic position and imbedded within the Cretaceous.

Discussions

The Souk Ahras basin architecture displays a northward deepening of paleo-environment since at least the Aptian which is the oldest strata of the basin. Biostratigraphic analyzes show that the upper Cretaceous facies are made of limestone- dominated sequences. Until the Paleocene, the Souk-Ahras basin is the hinge zone between a deep basin to the north and

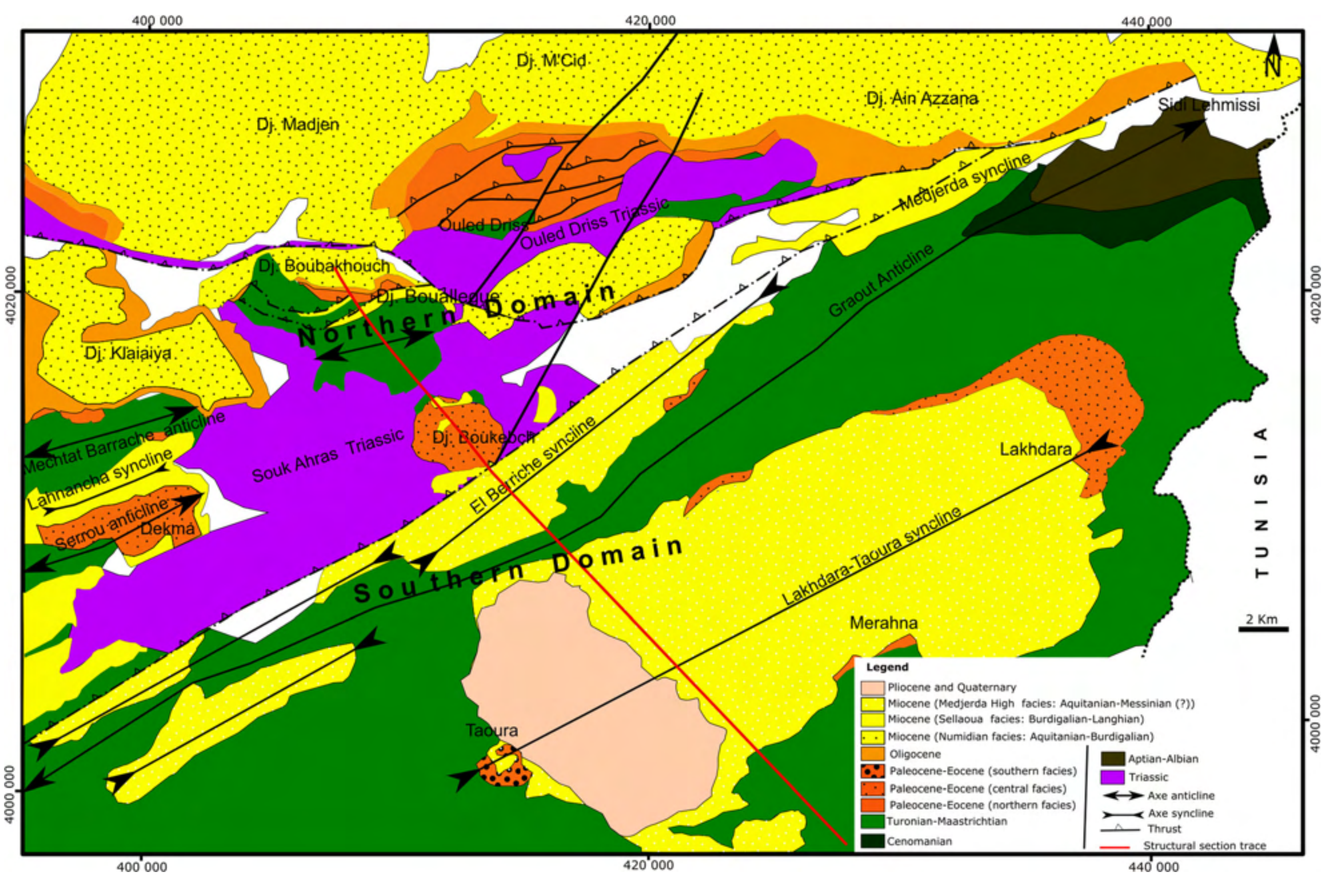


Fig. 15 Structural map of study area showing the structural synthetic cross section

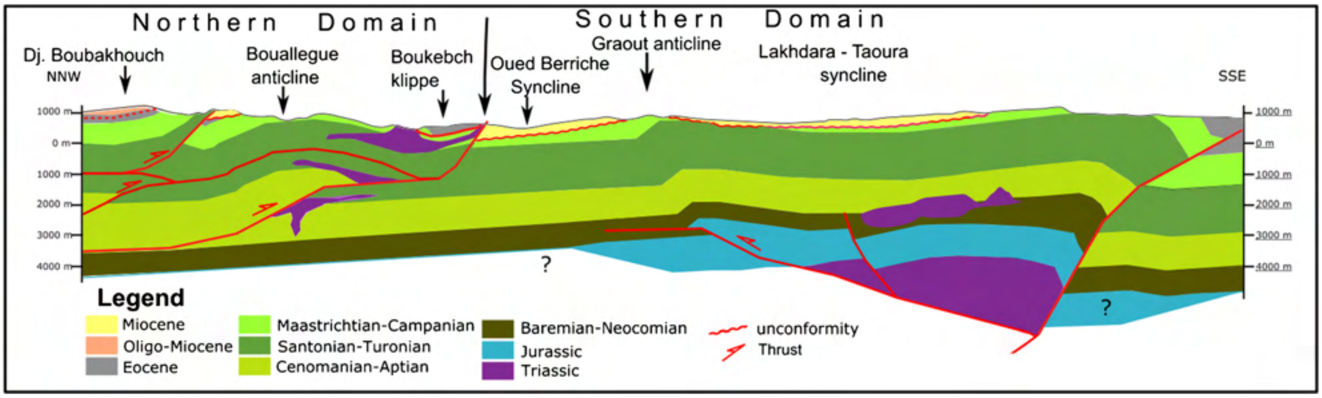


Fig. 16 Synthesized structural cross section across the mains structural domains of Souk Ahras area

carbonate ramp to the south as planktonic fauna dominated. Since the Eocene (Ypresian), the architecture of the Souk Ahras basin became well-defined. The depositional profile shape indicates that the basin is submitted to flexural subsidence since this time in response to foreland basin systems emplacement. The foredeep depozone was constituted by the deep-sea facies of globigerinid mudstones with yellow pillows of in the northern part laterally replaced by nummulitic and lumachellic facies in the center (Dj. Boukebch and Dj. Dekma) and near shore facies in the Medjerda High (Taoura). East of Merahna-Taoura syncline, this lateral shift of facies defined the northern side of a forebulge which became subaerial to the south where Eocene is absent.

The Oligocene sequence are formed by mudstones with rare agglutinated foraminifera, this facies indicates a rapid deepening of depositional environments particularly in the northern domain. It predated the occurrence of silico-clastics of the Miocene, which consisted of three facies roughly equivalent in time. In the northern domain, The Numidian sandstones are made-of base-of-slope facies. They consist of olistoliths and conglomerates inbedded in a clay matrix which contains Aquitanian-Burdigalian fauna. Sandstones beds are encountered and have been interpreted as turbidites s.l. (Raoult 1976; Rouvier 1977; Durand-Delga 1980; Vila 1980; Khomsi et al. 2009; Riahi et al. 2010). In the southern domain, the Miocene consists of conglomerates and breccias and ended by brownish clays, marls and glauconitic sandstone. This records the transgression during the Upper Burdigalian over the subaerial unconformity of the previous forebulge. in the Medjerda High the Miocene starts with 10–20m thick of Aquitanian sandstone bar and continues with 500m of Burdigalian-Langhian alternating sandstones and mudstones, then by 400m thick of Serravallian-Tortonian mudstones and topped by 300m of bioclastic limestones, conglomerates and clays containing lenses of gypsum affected to Tortonian-Messinian. In this later area, the Miocene records the acceleration of the subsidence due to flexural loading and the development of a backbulge depozone where a shallow marine environment dominates.

Cenozoic geodynamic evolution and tectonic events of Souk Ahras Sellaoua fold-thrust belt and its neighboring area

After a long period of extensional tectonic (90 million years) due to the divergence between the African and Eurasian plates which started in the Bajocian (lower – middle Jurassic time) and ended in the Coniacian age (upper Cretaceous) (Leprêtre et al. 2018). During the extensional period, Souk Ahras basin exhibited muddy facies rich in planktonic foraminiferal assemblage interbedded with rare limestones and fine-grained sandstone in a shelfal to slope environments. Farther south in the Medjerda High, diapiric structures were developing inducing facies and thickness variations. Northward, in the Tellian domain Cretaceous deposits are represented by mudstones and limestone rich in ammonites (David 1956; Chouabbi 1987; Lahondère 1987). Farther north, in the Flyschs domains, rhythmic sequences of clayey sandstone were accumulated (Raoult 1976) in deeper basin.

The inversion tectonic began in the Santonian age (Leprêtre et al. 2018), it was linked to the convergence between Africa and Eurasia follows a counter-clockwise rotation (Leprêtre et al. 2018). During the period, lasting from Santonian to upper Maastrichtian, there is no evidence of compressional event in Souk Ahras domain. The Emcherien event which is mentioned by many authors in the Constantinois, the Aurès, and Atlasic domains (Herkat and Guiraud 2006; Marmi and Guiraud 2006; Benaouali-Mebarek et al. 2006). This record is not recognized in the Souk Ahras basin and the sedimentary succession is muddy. Since the Santonian to lower Middle-Maastrichtian, it became dominated by chalky bars of limestone alternating with muddy-limestone levels rich in. The overall Campanian-Maastrichtian succession is shallowing-upward. Paleocene and Eocene deposits recorded the occurrence of large wavelength tectonics owing to the loading of internal zones. This basin configuration indicates that the Souk Ahras basin must be considered as a hinge zone between a southern flexural uplifted zone, Medjerda High and a northern foredeep depozone in the Tellian domain. The Oligo-Miocene period is characterized a renewing of such northern loading in a filled state until the Langhian when the marine sedimentation ended. Then short wavelength tectonic propagated in the Souk Ahras basin. This thin-skinned tectonics involved Mesozoic strata which were previously dominated by salt tectonics. Therefore Triassic materials are also present. The structural position of such evaporites is subjected to a large debate salt tectonics vs. salt sedimentation. The map extension of the Triassic bodies (8% of map area), the economic interest of such indices for metalogenic or hydrocarbon exploration mask the relevant data, which may explain the occurrence of such evaporitic bodies. The Jurassic and Lower Cretaceous strata are not associated with Triassic bodies. Contacts between evaporite bodies and host rocks cannot be typified as they have been observed as stratigraphic (diapir welds, salt canopy and/or glacier) or faulted (salt sheets, thrust ramps). Diapirism occurred in the whole Maghrebian domain from the Central High Atlas of Morocco (Vergés et al. 2017) to the Tunisia Tell-Atlas. In Tunisia the so-called “Zones des Dômes” has been described subjected to salt tectonics since the late Aptian (Perthuisot 1978) and ending in the Albian (Vila 1995; Vila et al. 1996), therefore, this framework predated the occurrence of contraction in the Souk Ahras area. Triassic bodies at the boundary of which thrust faults are inferred, cannot be branched onto a regional decollement nor interpreted as merging hangingwall flats because the Jurassic is absent, If any, they can be associated with secondary thrust-systems. Their occurrence within middle Miocene strata should result from squeezing of salt tectonics features hosted within upper Cretaceous units and totally unrooted from their source-fed.

Conclusions

Stratigraphic and biostratigraphic analysis of Souk Ahras fold-and-thrust belt show 4000m thick of carbonate series rich in Planktonic foraminifera associated with benthic foraminifera and Ostracods, ranging in age from Aptian to Priabonian age. They are unconformably overlain by a detrital Miocene series of 500 m to 1200 m thickness.

The dominance of planktonic foraminiferal assemblage on benthic foraminiferal assemblage within Cretaceous strata reveals that it is a marine deposition environment of outer shelf.

The distribution of Eocene–Oligocene deposits under the lower-middle Miocene (Langhian–Burdigalian age) indicates a large uplift during this period. This uplift corresponds to the Atlasic phase of the authors, which is well recognized in the Maghrebides thrust belt and predated the emplacement of the Tell units (Vila 1980; Benaouali-Mebarek et al. 2006; Roure et al. 2012; Khomsi et al. 2016; Leprêtre et al. 2018). This event is recorded a major reorganization at the plate boundary between Africa and Eurasia (Roure et al. 2012; Leprêtre et al. 2018).

The unconformable Miocene in the Sellaoua basin indicates the southeastward migration of flexural subsidence. Tectonic-sedimentation relationships displays the transition from a foredeep depozone in the north a forebulge depozone in the Sellaoua basin and a backbulge depozone above the Medjerda High. As thrust systems propagates in an overall break-forward sequence to the southeast. In the footwall of such thin-skinned thrust-wedge (Tellian thrust sheets), thick-skinned positive inversion feature are observed (Medjerda High).

Triassic occurrences are inherited from the passive margin geodynamics until the Albian and latter involved in the structural units.

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Data Availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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